ENG 3165 LECTURE 11

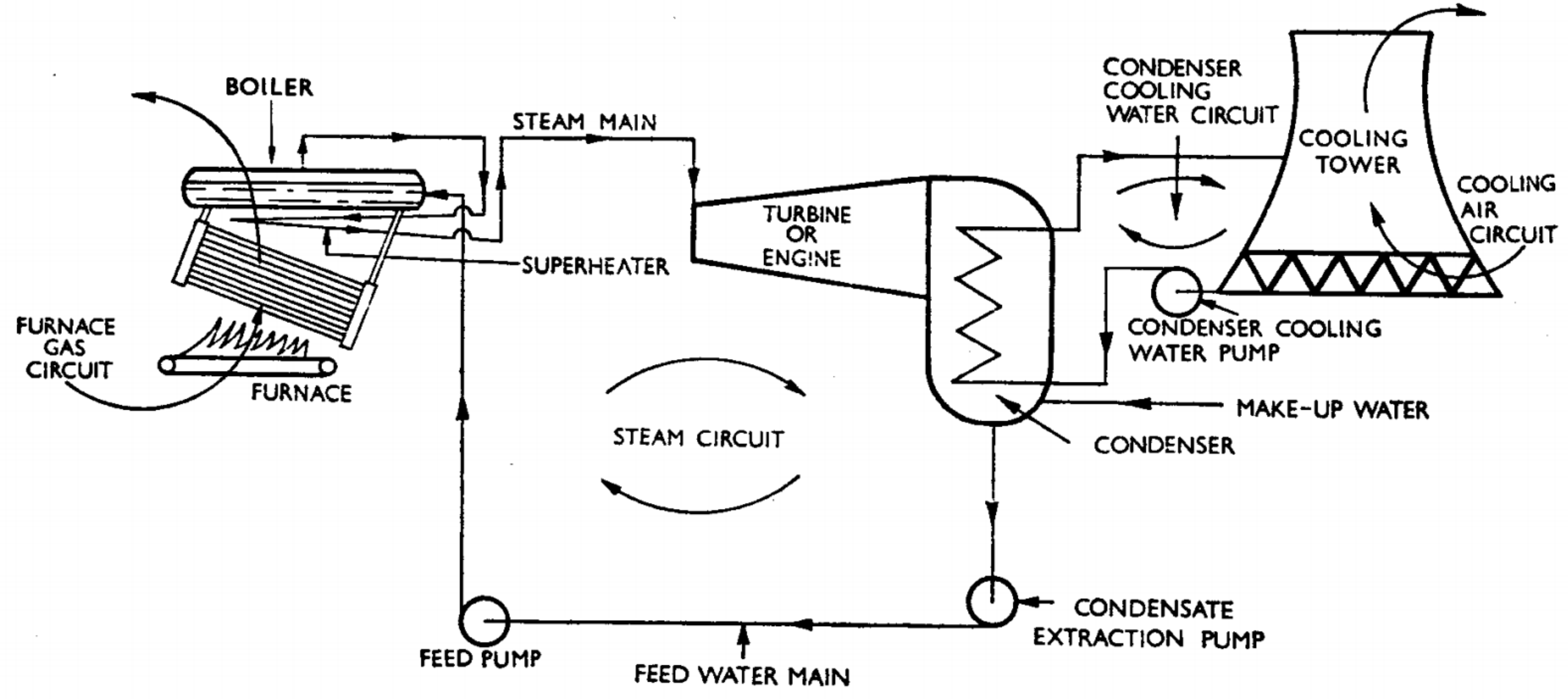
THERMODYNAMICS COMPONENT

The Steam Plant (Thermal Power Plant)

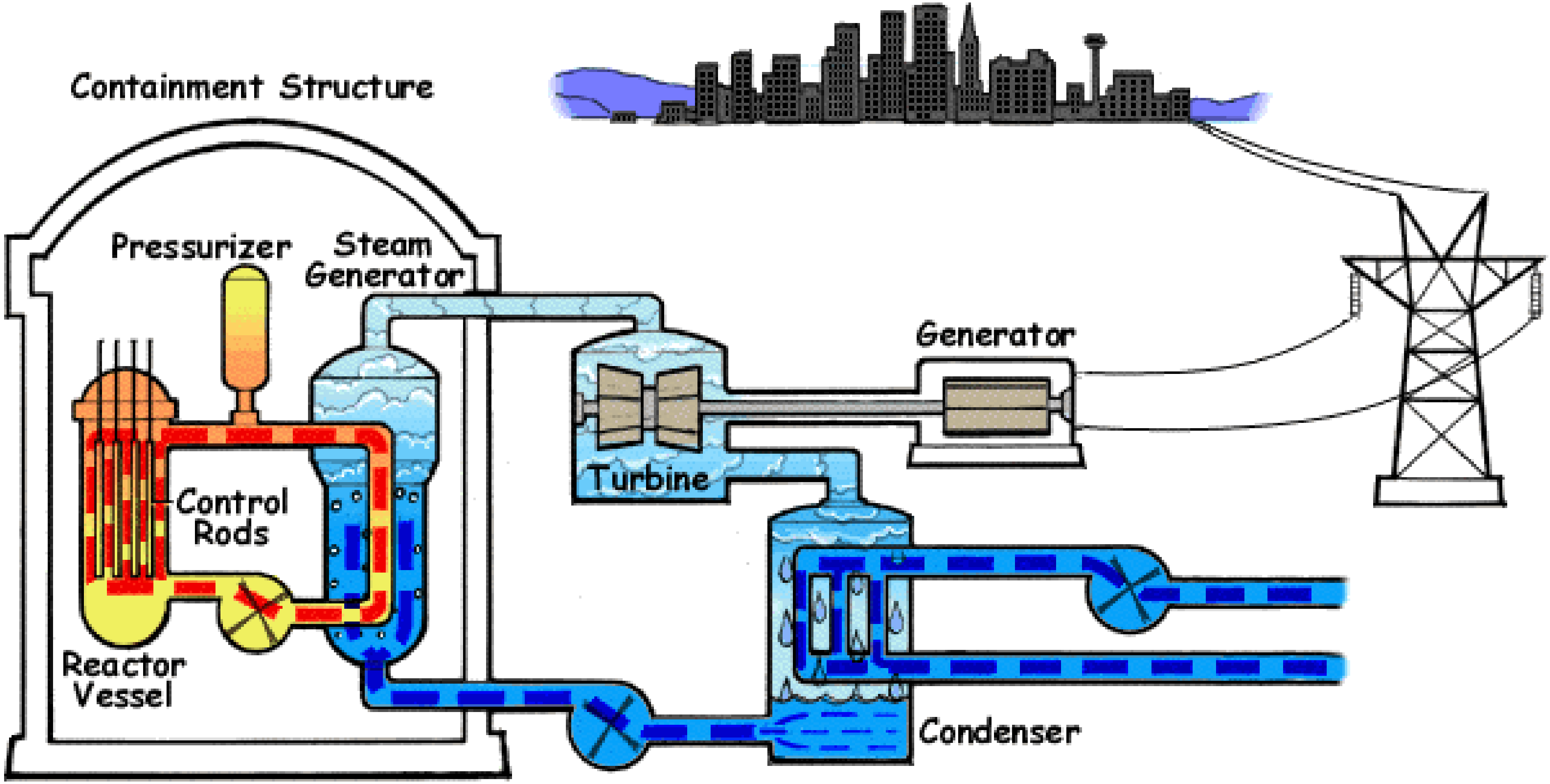
Introduction

- A steam power plant continuously converts the energy stored fossil fuels (coal, petroleum, and natural gas) or fissile fuels (uranium, thorium) OR other energy resources in to shaft work and ultimately into electricity.
- Steam power plants are commonly referred to as coal plants, nuclear plants, or natural gas plants, depending on the type of fuel used to supply heat to the steam.

GENERAL INTRODUCTION



GENERAL INTRODUCTION



GENERAL INTRODUCTION

- Steam is generated in a **boiler** from which it passes into the **steam main.** The steam main feeds the steam into a **turbine** or **engine** or it may pass into some other plant such as **heaters** or **process machinery**.
- After expanding through the turbine or engine or passing through some other plant, if the plant is working on a **'dead-loss' system**, then the exhaust steam passes away to atmosphere. Such is the case with the steam locomotive which is still in use on many railways in many countries of the world. This system is very inefficient and is rarely adopted in modern plant.
- It is used in the steam locomotive since, in this case, the plant is mobile and there is not sufficient room for the complex **steam recovery equipment** which can be installed in a power station or factory.

GENERAL INTRODUCTION

- If steam recovery plant is installed then the **exhaust steam** passes into a **condenser** where it is condensed to water, called **condensate**. The condensate is extracted from the condenser by the **condensate extraction pump** from which it passes as **feed water** into the **feed water main** and back to the boiler.
- Because the boiler is operating at a **high pressure** the water pressure must be increased in order to get it into the boiler. This is dealt with by means of a pump called the **feed pump**.
- Thus the water returns to the boiler and it will be noted that, neglecting losses in the system, with a steam recovery plant, it is the same water being circulated all the time. Actually, there are losses and this is made up in the condenser by means of a **make-up water supply**.

GENERAL INTRODUCTION

The advantages of steam recovery plant are primarily as follows:

1. Firstly, the pressure in the condenser can be operated well below atmospheric pressure. This means that a greater expansion of the steam can be obtained which results in more work.

2. Secondly, the water in the circuit can be chemically treated to reduce scale formation in the boiler. The formation of scale in the boiler impedes the transfer of heat from the furnace to the water and hence results in a reduction of boiler efficiency. It may further result in local overheating with resultant damage and it may even cause a burst in the vicinity if overheating is serious.

- The condenser is cooled by circulating cooling water through it. If an abundant supply of water is nearby, such as from a river or lake, then this can be used. Filters are usually installed to cut down water pollution, otherwise the condenser cooling water circuit may become blocked.

GENERAL INTRODUCTION

- On the other hand, the river or lake may itself become polluted by hot water returning from the condenser. If the amount of hot water is large it could have an effect on the flora and fauna of the river or lake.
- If a river or lake is available or the risk of pollution is too high then it is common to install a cooling tower which is made of either wood or concrete. The hot water from the condenser is passed into the tower approximately mid-way up where it is sprayed to the bottom.
- Air circulates into the bottom of the tower and passes up through the water spray. Heat transfer occurs between the water and the air thus cooling the water. The warmed air passes out at the top of the tower.
- The cooled water is collected at the bottom of the tower from where it is pumped back to the condenser. With this method it will be noted that it is the same cooling water being circulated through the condenser. It is only necessary to make up any loss

GENERAL INTRODUCTION

Looking at the steam plant system as a whole, note that there are four separate circuits:

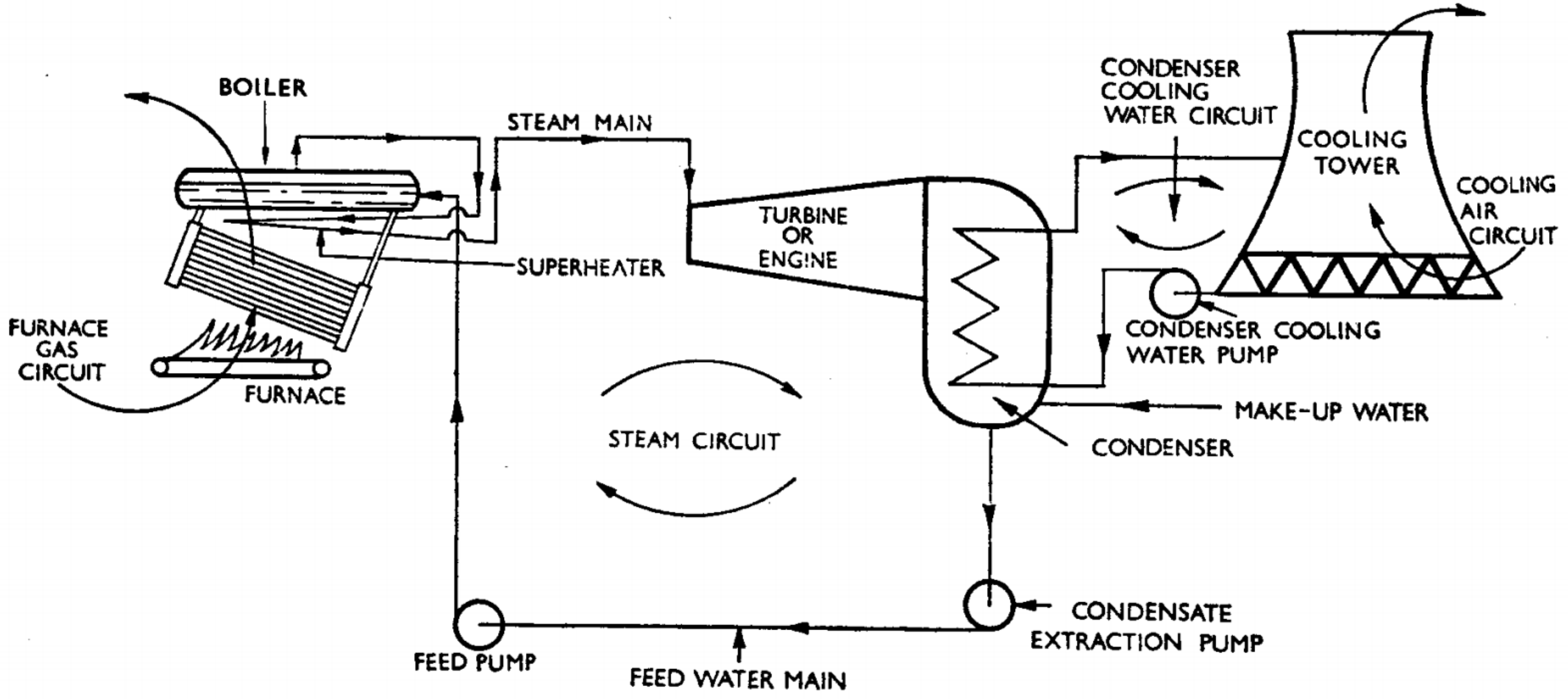
1. **The furnace gas circuit:** Air is taken into the furnace from the atmosphere to supply the necessary oxygen for combustion. The combustion products pass through the boiler, transferring heat, and then pass out to the atmosphere through the flue. Care should be taken to reduce atmospheric pollution from the combustion products to an absolute minimum.
2. **The steam circuit:** Water is passed into the boiler in which it is converted into steam. It passes into the plant in which it is expanded giving up some of its energy. {is then condensed in a condenser from which it passes as condensate to be pumped back into the boiler.

GENERAL INTRODUCTION

3. Condenser cooling water circuit: Cool water passes into the condenser, has heat transferred into it by the condensing steam and then, at a higher temperature, passes out to be cooled in a river, lake or cooling tower. cool water then circulates back to the condenser. Here again, care must be taken to reduce pollution to a minimum if the discharge of condenser cooling water is into a river or a lake.

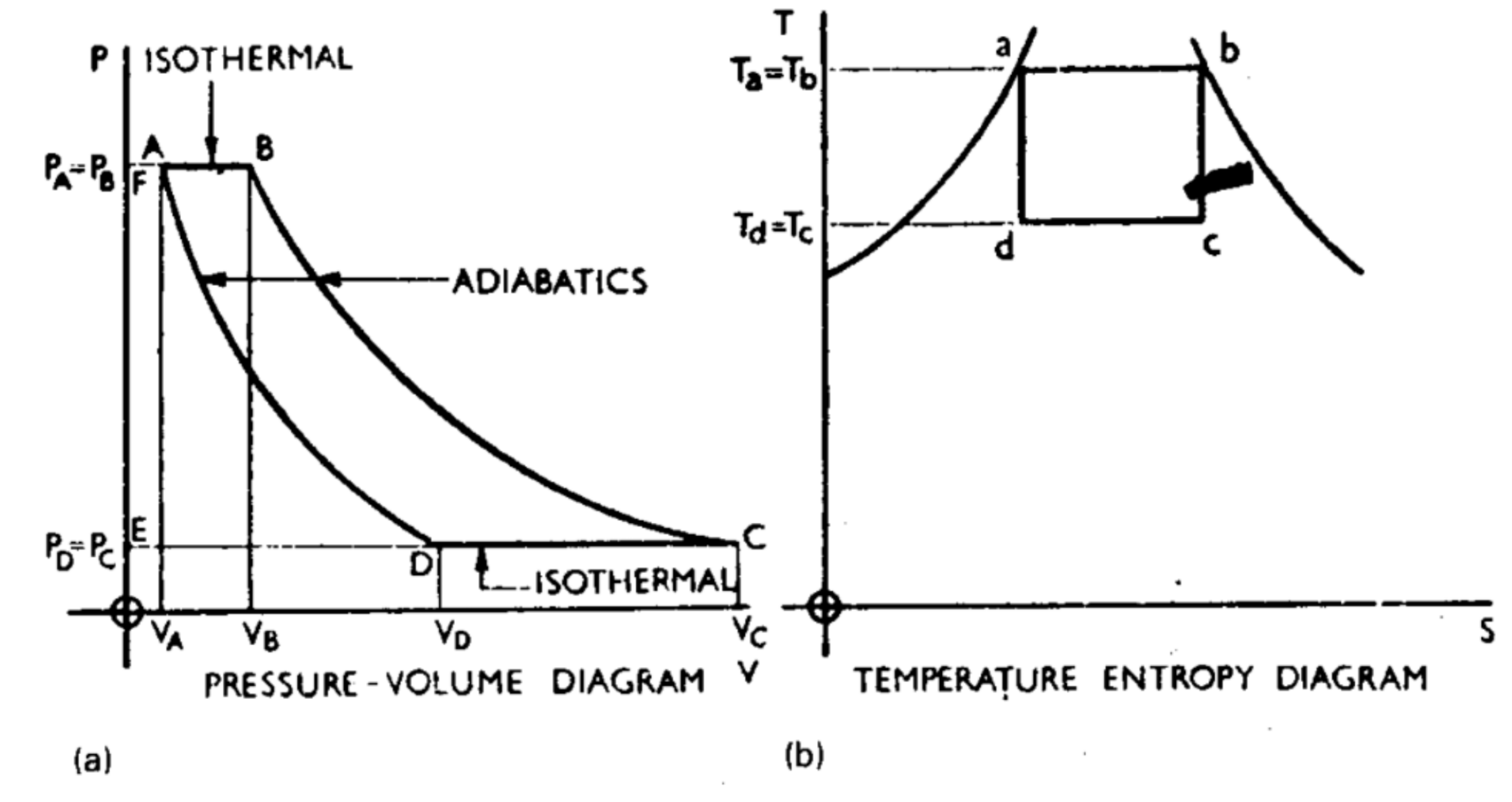
4. Cooling air circuit: Case of a cooling tower, cool air passes into the bottom of the tower from the atmosphere and heat is transferred into it from the falling hot water spray. The warm air then passes back to the atmosphere through the top of the tower. In the case of a river or lake the condenser cooling water will mix with river or lake water which will be cooled by heat transfer to the atmosphere. It should be mentioned here that in some steam plant the condensate from the condenser is passed into a tank, called the hot well, which acts as a reservoir for feed water. From the hot well, feed water is pumped through the feed pump back into the boiler. In this case, make-up water could be fed into the hot well

GENERAL INTRODUCTION



THE CARNOT CYCLE AND THE STEAM PLANT

- To operate the Carnot cycle in a steam plant the processes would be as follows. Consider the P-V diagram first:



THE CARNOT CYCLE AND THE STEAM PLANT

A–B Water at boiler pressure P_B and volume V_A is fed from the feed pump into the boiler. This is shown as process AF. In the boiler, the water is converted into steam at pressure P_B. The volume of the steam produced is V_B. This volume of steam V_B is then fed from the boiler into the engine or turbine. This is shown as process FB.

Now the conversion of water into steam at constant pressure takes place at constant temperature, the saturation temperature T_B. This is so long as the steam does not enter the superheat phase. Hence, if the steam produced is either wet or dry saturated, then this process is isothermal.

B–C The steam is expanded frictionless adiabatically in the engine or turbine.

C–D The steam, after expansion, is passed from the engine or turbine into a condenser. This is shown as process CE. In the condenser the volume of the steam is reduced from V_C to V_D.

THE CARNOT CYCLE AND THE STEAM PLANT

It takes place at constant condenser pressure P_C and at constant condenser saturation temperature T_C. This process is therefore isothermal.

D–A The partially condensed steam at pressure P_C and volume V_D is fed from the condenser into the feed pump. This is shown as process ED. In the feed pump the steam is compressed frictionless adiabatically to boiler pressure P_B. This is shown as process DA. The compression converts the wet steam at condenser pressure into water at boiler pressure. This water is fed into the boiler, shown as process AF and the cycle is repeated.

THE CARNOT CYCLE AND THE STEAM PLANT

Now the P–V diagram is really composed of two diagrams.

There is the engine or turbine diagram FBCE whose area will give work output. There is also the feed pump diagram EDAF whose area will give the required work input to run the feed pump.

The net work output from the plant will, therefore, be the net area of these two diagrams. This is the area ABCD.

This area ABCD is enclosed by two isothermal processes and two adiabatic processes. Hence, this is a Carnot cycle. Its thermal efficiency will be given by $(T_B - T_C)/T_B$ which is the maximum efficiency possible between these temperature limits (see section 13.2).

The T–s diagram of the cycle is shown in Fig. 8.19(b).

a–b represents the constant temperature formation of the steam in the boiler.

b–c represents the frictionless adiabatic (isentropic) expansion of the steam in the engine or turbine.

c–d represents the condensation of the steam in the condenser.

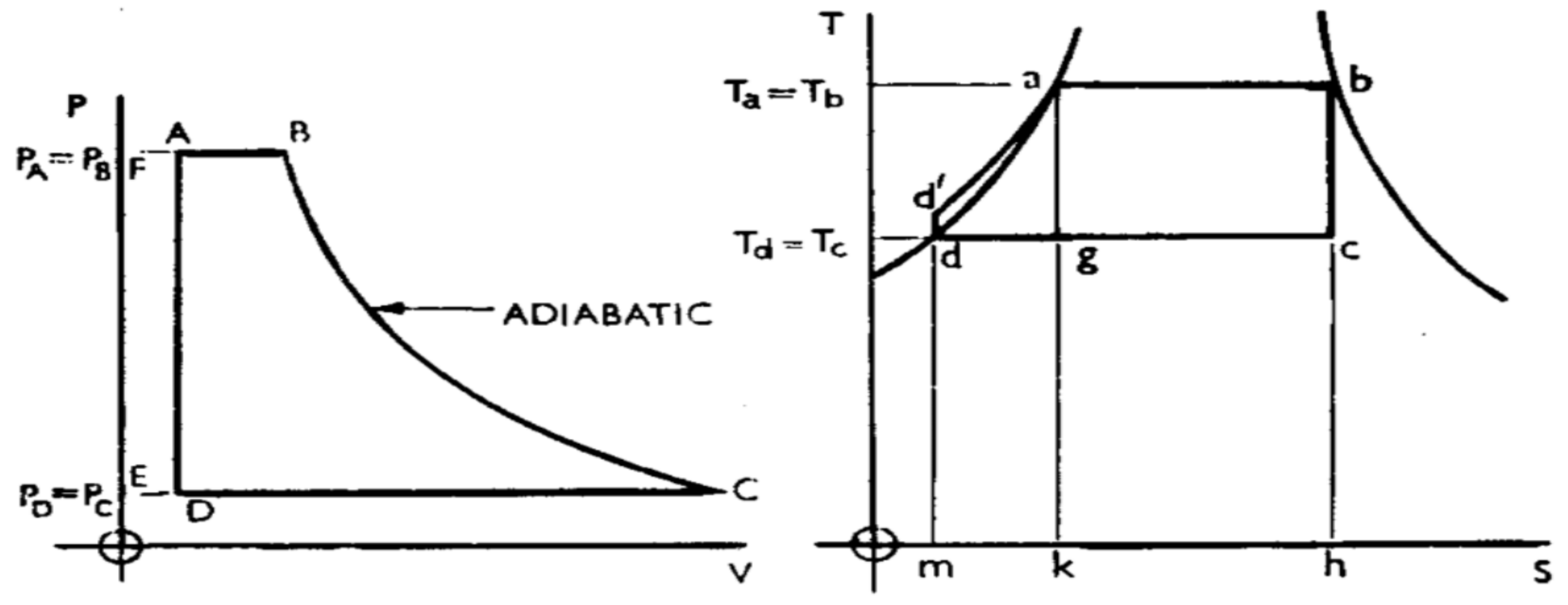
d–a represents the frictionless adiabatic (isentropic) compression of the steam in the feed pump back to water at boiler pressure at 'a'.

THE CARNOT CYCLE AND THE STEAM PLANT

- Now this cycle for operation in a steam plant is practical up to a point. The isothermal expansion of the steam in the boiler and the adiabatic expansion of the steam in the engine or turbine (more especially in turbines) is reasonable.
- The impractical part is in the handling of the steam in the condenser and feed pump. In the condenser, the steam is only partially condensed and condensation must be stopped at d. Also the feed pump must be capable of handling both wet steam and water.
- A slight modification to this cycle, however, will produce a cycle which is more practical although it will have a reduced thermal efficiency. This cycle is the **Rankine cycle** and is the usually accepted ideal cycle for steam plant.

THE RANKINE CYCLE

- The modification made to the Carnot cycle to produce the Rankine cycle is that instead of stopping the condensation in the condenser at some intermediate condition, the condensation is completed. On the T-s diagram, the Carnot cycle would be abcg. For the Rankine cycle, however, condensation is continued until it is complete at d. At this point there is all water. This water can be successfully dealt with in a feed pump in which its pressure can be raised in feeding it back into the boiler. The cycle thus becomes more practical.



PRESSURE–VOLUME DIAGRAM
(a)

TEMPERATURE–ENTROPY DIAGRAM
(b)

THE RANKINE CYCLE

- This is shown exaggerated as process **d-d'** on the T-s diagram.
- In the boiler the temperature of the water is raised at boiler pressure, shown as process **d'-a** and thus the cycle is completed.
- The complete Rankine cycle is, therefore, **abcdd'a**.
- On the P-V diagram, there are two cycles:

  i) The work done in the engine or turbine is represented by the area FBCE.

  ii) There is also the feed pump work and this is represented by the area EDAF.

  iii) The feed pump work is negative since work must be put into the pump.

Hence, $$Work\ Done/Cycle = Area\ ABCD \qquad (1)$$

- Using the steady-flow equation and neglecting changes in potential and kinetic energy, then, since for an adiabatic expansion $Q = 0$, the energy equation for an adiabatic expansion becomes,

$$h_1 = h_2 + W \qquad (2)$$

THE RANKINE CYCLE

or

$$\text{Specific W} = h_1 - h_2 \tag{2}$$

Using symbols as in Fig. 8.20, then,

$$\text{Specific W} = h_b - h_c$$

$$= \text{area FBCE on } P\text{–}V \text{ diagram} \tag{3}$$

$$\text{The feed pump work/unit mass} = \text{Area EDAF}$$

$$= (P_B - P_C)v_D \tag{4}$$

Hence,

$$\text{Net work done/cycle} = (h_b - h_c) - (P_B - P_C)v_D \tag{5}$$

Now the heat transfer required in the boiler to convert the water at d′ into steam at b

$$= h_b - h_{d'} \tag{6}$$

But the total energy of the water entering the boiler at d′

$$= \text{liquid enthalpy at d} + \text{Feed-pump work}$$

or

$$h_{d'} = h_d + (P_B - P_C)v_D \tag{7}$$

THE RANKINE CYCLE

Substituting equation (7) in equation (6)

Heat transfer required in boiler

$$= h_b - \{h_d + (P_B - P_C)v_D\}$$
$$= (h_b - h_d) - (P_B - P_C)v_D \qquad (8)$$

Now, thermal efficiency of cycle

$$= \frac{\text{Work done/cycle}}{\text{Heat received/cycle}}$$

Hence, from equations (5) and (8),

Thermal efficiency of Rankine cycle

$$= \frac{(h_b - h_c) - (P_B - P_C)v_D}{(h_b - h_d) - (P_B - P_C)v_D} \qquad (9)$$

The feed pump term $(P_B - P_C)v_D$, is, however, small compared with the other energy quantities and hence it can be sensibly neglected.

THE RANKINE CYCLE

Thus, equation (9) becomes,

Thermal, or now, the Rankine efficiency

$$= \frac{(h_b - h_c)}{(h_b - h_d)} \tag{10}$$

The cycle is named after William John Rankine (1820–72), a Glasgow University Professor.

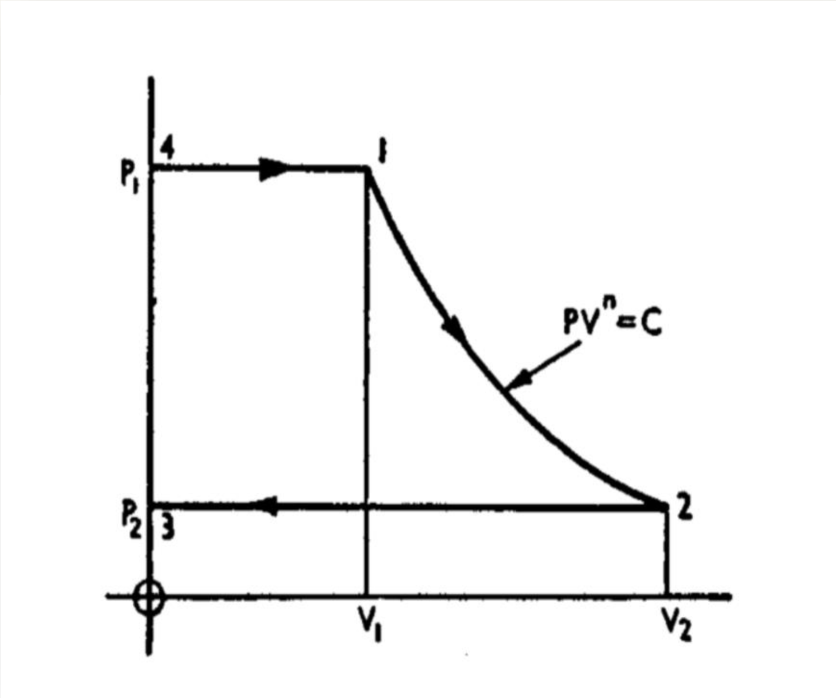
If the work done by the feed pump is neglected and assuming that the steam expansion can be expressed in the form $PV^n = \text{constant}$, then the P–V diagram for the Rankine cycle is as shown in Fig. 8.21. From this diagram.

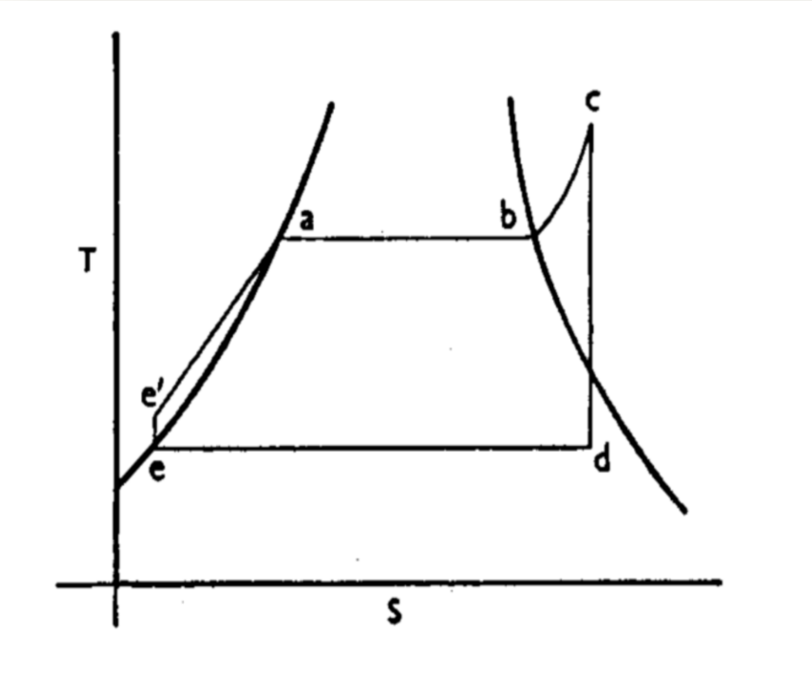
$$\begin{aligned}
\text{Work done} &= \text{Area under 4–1} + \text{area under 1–2} \\
&\quad - \text{area under 2–3} \\
&= P_1V_1 + \frac{(P_1V_1 - P_2V_2)}{n-1} - P_2V_2 \\
&= (P_1V_1 - P_2V_2) + \frac{(P_1V_1 - P_2V_2)}{n-1} \\
&= (P_1V_1 - P_2V_2)\left(1 + \frac{1}{n-1}\right) \\
&= (P_1V_1 - P_2V_2)\frac{(n-1)+1}{n-1}
\end{aligned}$$

$$\text{Work done} = \frac{n}{n-1}(P_1V_1 - P_2V_2) \tag{11}$$

SUPER-HEATED STEAM CYCLE

- If superheated steam is used in the Rankine cycle then the appearance of the cycle on the T-s diagram is as shown. The difference between this diagram and the previous one, is the inclusion of the superheat line *b-c*. The complete cycle is now *abcdee'*





THE RANKINE CYCLE

- The thermal efficiency has the same form as before. Using the lettering of:

$$\eta_{TH,Rankine} = \frac{h_c - h_d}{h_C - h_e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

- There is little gain in thermal efficiency as a result of using superheated steam over that of using saturated steam.
- The chief advantage of using superheated steam are:

  i) Little or no condensation loss in transmission.

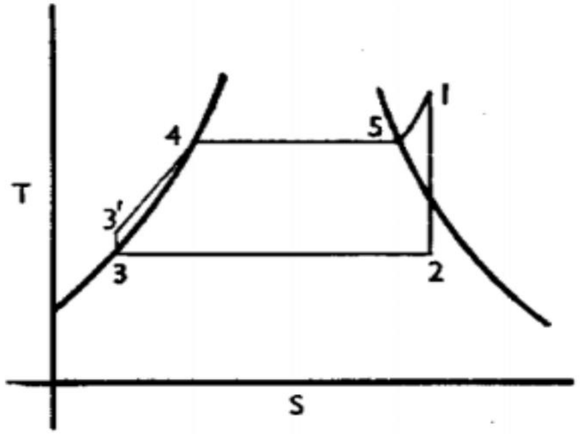
  ii) Greater potential for enthalpy drop and hence for work done.

- Note, also, that by using superheated steam, there is a further departure from the Carnot cycle since the final temperature of the steam is above the constant saturation temperature of the boiler.
- Also Rankine cycle will have a high work ratio (→ unity), since the net work done/cycle is very close to the positive work done/cycle, the feed pump work being very low by comparison.
- Also, the Rankine cycle will have a higher work ratio than the Carnot vapour cycle.

Example

A steam turbine plant operates on the Rankine cycle. Steam is delivered from the boiler to the turbine at a pressure of 3·5 MN/m^2 and with a temperature of 350°C. Steam from the turbine exhausts into a condenser at a pressure of 10 kN/m^2. Condensate from the condenser is returned to the boiler by means of a feed pump. Neglecting losses, determine,

(a) the energy supplied in the boiler/kg of steam generated,
(b) the dryness fraction of the steam entering the condenser,
(c) the Rankine efficiency.



(a) Energy supplied in boiler/kg steam = $(h_1 - h_3)$.
At 3∂5 MN/m² and 350°C.

$$h_1 = 3\,139 - \frac{1{\cdot}5}{2}(3\,139 - 3\,095) = 3\,139 - \left(\frac{1{\cdot}5}{2} \times 44\right)$$

$$= 3\,139 - 33 = \underline{3\,106 \text{ kJ/kg}}$$

At 10 kN/m², $h_3 = \underline{191{\cdot}8 \text{ kJ/kg}}$

$\therefore\ h_1 - h_3 = 3\,106 - 191{\cdot}8 = \underline{2\,914{\cdot}2 \text{ kJ/kg}}$

This is the energy supplied in the boiler.

(b) Expansion through the turbine is theoretically isentropic, hence $s_1 = s_2$.

$$s_1 = 6{\cdot}960 - \frac{1{\cdot}5}{2}(6{\cdot}960 - 6{\cdot}587) = 6{\cdot}960 - \left(\frac{1{\cdot}5}{2} \times 0{\cdot}373\right)$$

$$= 6{\cdot}960 - 0{\cdot}28 = \underline{6{\cdot}680\ \text{kJ/kg K}}$$

$$s_2 = s_{f2} + x_2(s_{g2} - s_{f2}) = 0{\cdot}649 + x_2(8{\cdot}151 - 0{\cdot}649) = 6{\cdot}680$$

$$\therefore\ x_2 = \frac{6{\cdot}680 - 0{\cdot}649}{8{\cdot}151 - 0{\cdot}649} = \frac{6{\cdot}031}{7{\cdot}502} = \underline{0{\cdot}804}$$

This is the dryness fraction of the steam entering the condenser.

(c) Rankine $\eta = \dfrac{(h_1 - h_2)}{(h_1 - h_3)}$

$$h_2 = h_{f2} + x_2 h_{fg2} = 191{\cdot}8 + (0{\cdot}803 \times 2\,392{\cdot}9)$$

$$= 191{\cdot}8 + 1\,921{\cdot}5 = \underline{2\,113{\cdot}3\ \text{kJ/kg}}$$

$$\therefore \text{ Rankine } \eta = \frac{3\,106 - 2\,113{\cdot}3}{3\,106 - 191{\cdot}8}$$

$$= \frac{992{\cdot}7}{2\,914{\cdot}2} = \underline{0{\cdot}341}$$

$$= 0{\cdot}341 \times 100$$

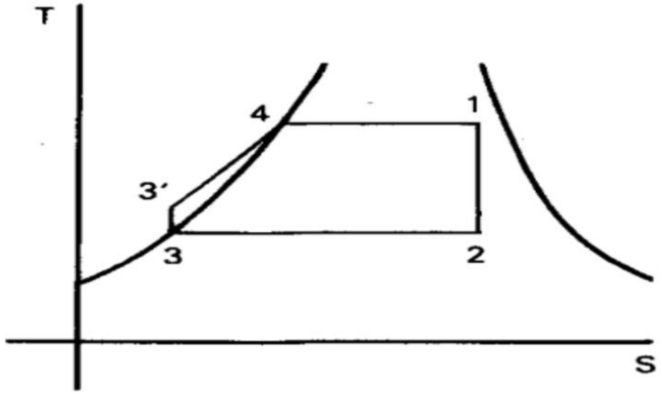
$$= \underline{34{\cdot}1\,\%}$$

Example

A steam plant operates on the Rankine cycle. Steam is supplied at a pressure of 1 MN/m^2 and with a dryness fraction of 0·97. The steam exhausts into a condenser at a pressure of 15 kN/m^2. Determine,

(a) the Rankine efficiency,

(b) if the expansion of the steam is assumed to follow the law $PV^{1.135} = C$, estimate the specific work done and compare this with that obtained when determining the Rankine efficiency.



$$h_1 = 762{\cdot}6 + (0{\cdot}97 \times 2\,013{\cdot}6) = 762{\cdot}6 + 1\,953{\cdot}2$$

$$= \underline{2\,715{\cdot}8 \text{ kJ/kg K}}$$

$$s_1 = 2{\cdot}138 + 0{\cdot}97(6{\cdot}583 - 2{\cdot}138) = 2{\cdot}138 + (0{\cdot}97 \times 4{\cdot}445)$$

$$= 2{\cdot}138 + 4{\cdot}332 = \underline{6{\cdot}470 \text{ kJ/kg K}}$$

$$s_1 = s_2$$

$$\therefore\ 6{\cdot}470 = 0{\cdot}755 + x_2(8{\cdot}009 - 0{\cdot}755)$$

$$x_2 = \frac{6{\cdot}470 - 0{\cdot}755}{8{\cdot}009 - 0{\cdot}755} = \frac{5{\cdot}715}{7{\cdot}254}$$

$$= \underline{0{\cdot}788}$$

$$h_2 = 226{\cdot}0 + (0{\cdot}788 \times 2\,373{\cdot}2) = 226{\cdot}0 + 1\,870{\cdot}1$$

$$= \underline{2\,096{\cdot}1 \text{ kJ/kg}} \text{ K}$$

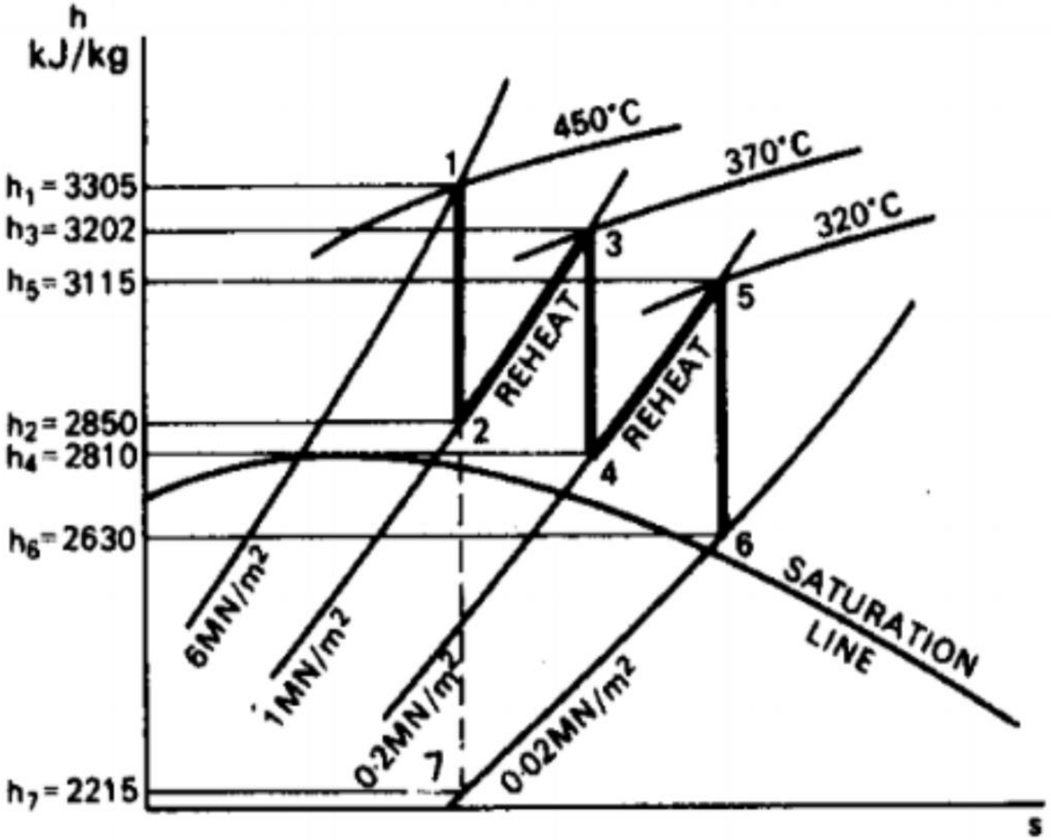
THE RE-HEATING CYCLE OF THE STEAM PLANT

- The pressure ratio through the turbine can be considerable. A
- Any superheated steam supplied would soon become wet after partial expansion.
- Wet steam passing over turbine blades for long time periods will produce some corrosion and erosion of the blades.
- To avoid this, if the superheated steam, after partial expansion in the turbine, is passed back to the boiler to be reheated at constant pressure to a higher temperature and then passed back to the turbine, the expansion which follows will be dry and superheated, thus largely eliminating the corrosion and erosion of the turbine blades.

Example

Steam is supplied to a turbine at a pressure of 6 MN/m^2 and at a temperature of 450°C. It is expanded in the first stage to a pressure of 1 MN/m^2. The steam is then passed back to the boiler in which it is reheated at a pressure of 1 MN/m^2 to a temperature of 370°C. It is then passed back to the turbine to be expanded in the second stage down to a pressure of 0·2 MN/m^2. The steam is then again passed back to the boiler in which it is reheated at a pressure of 0·2 MN/m^2 to a pressure of 320°C. It is then passed back to the turbine to be expanded in the third stage down to a pressure of 0·02 MN/m^2. The steam is then passed to a condenser to be condensed, but not undercooled, at a pressure of 0·02 MN/m^2 and the condensate is then passed back to the boiler. Assuming isentropic expansions in the turbine and using an enthalpy-entropy chart for steam, determine:

(a) the theoretical power/kg of steam/s passing through the turbine;
(b) the thermal efficiency of the cycle;
(c) the thermal efficiency of the cycle assuming there is no reheat.



(a) A sketch of the enthalpy-entropy chart is shown. From the chart the following values of specific enthalpy are obtained.

$h_1 = 3\,305$ kJ/kg
$h_2 = 2\,850$ kJ/kg
$h_3 = 3\,202$ kJ/kg

$h_4 = 2\,810$ kJ/kg
$h_5 = 3\,115$ kJ/kg
$h_6 = 2\,630$ kJ/kg
$h_7 = 2\,215$ kJ/kg

Specific work/kg steam passing through the turbine

$$= (h_1 - h_2) + (h_3 - h_4) + (h_5 - h_6)$$
$$= (3\,305 - 2\,850) + (3\,202 - 2\,810) + (3\,115 - 2\,630)$$
$$= 455 + 392 + 485$$
$$= \underline{1\,332 \text{ kJ}}$$

$\therefore$ Theoretical power/kg steam/s $= 1\,332$ kJ/s $= \underline{1\,332 \text{ kW}}$

(b) Thermal efficiency $= \dfrac{\text{Specific work}}{\text{Specific energy input}}$

$$= \frac{(h_1 - h_2) + (h_3 - h_4) + (h_5 - h_6)}{(h_1 - h_{f6}) + (h_3 - h_2) + (h_5 - h_4)}$$
$$= \frac{1\,332}{(3\,305 - 251{\cdot}5) + (3\,202 - 2\,850) + (3\,115 - 2\,810)}$$
$$= \frac{1\,332}{3\,053{\cdot}5 + 352 + 305}$$
$$= \frac{1\,332}{3\,710{\cdot}5}$$
$$= 0{\cdot}359$$
$$= 0{\cdot}359 \times 100 = \underline{35{\cdot}9\,\%}$$

Note that $h_{f6} = 251{\cdot}5$ kJ/kg is the specific liquid enthalpy at 0·02 MN/m^2 = 20 kN/m^2 and is obtained from steam tables.

(c) If there is no reheat,

$$\text{Thermal efficiency} = \frac{h_1 - h_7}{h_1 - h_{f7}}$$
$$= \frac{3\,305 - 2\,215}{3\,305 - 251{\cdot}5}$$
$$= \frac{1\,090}{3053{\cdot}5}$$
$$= 0{\cdot}357$$
$$= 0{\cdot}357 \times 100$$
$$= \underline{35{\cdot}7\%}$$

- Note that there is little difference in the thermal efficiency, but that the steam is at all times superheated in the case (a) when the steam is reheated.

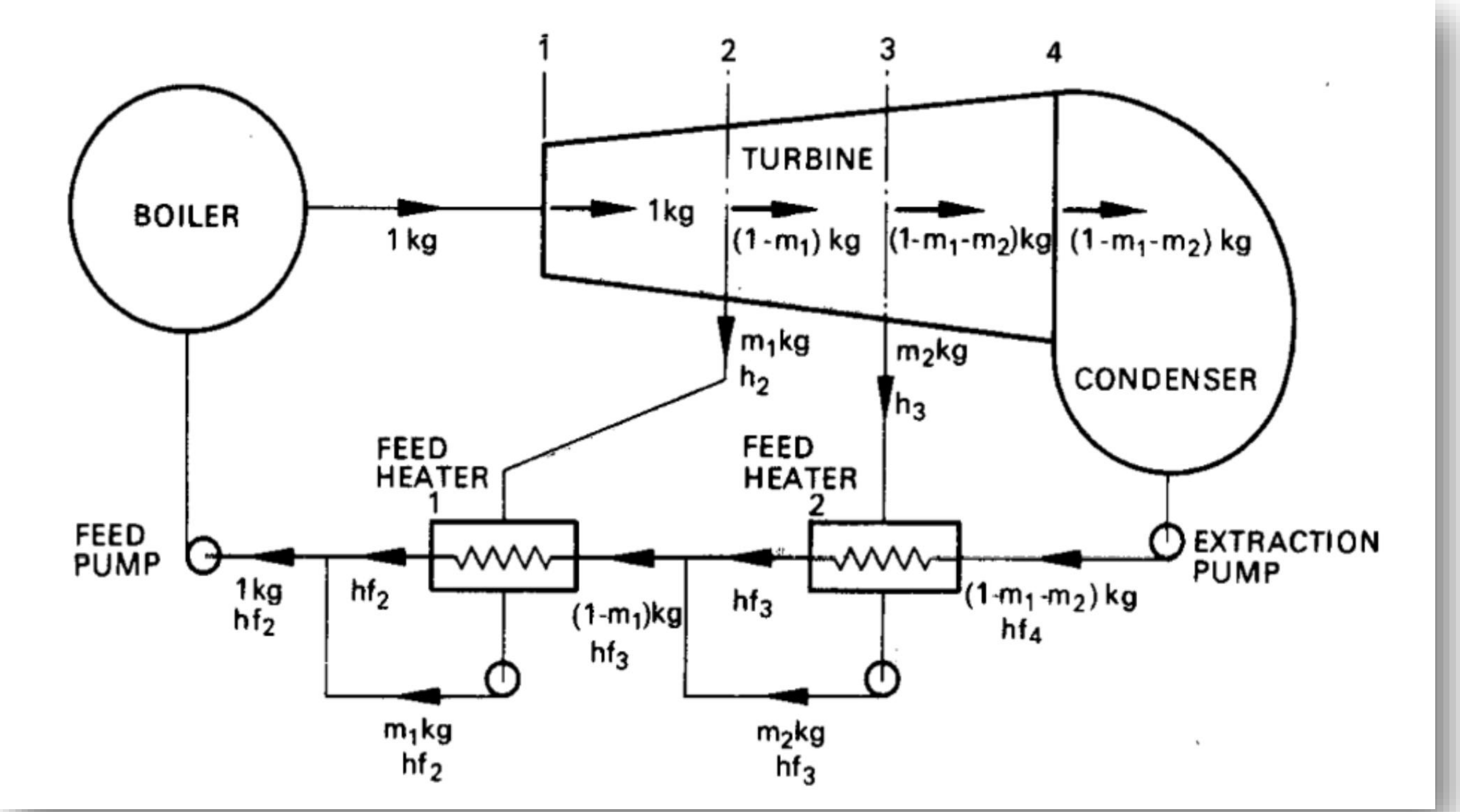
THE REGENERATIVE CYCLE

- To increase the feed water temperature on its way back to the boiler and, as a result, increase the thermal efficiency of the plant, the process of feed heating is introduced.
- In this process, small quantities of steam are bled at various stages through the turbine. The bled steam passes through a feed heater in which it condenses in a heat transfer process with the feed water.
- Thus the temperature of the feed water is increased. The condensate from the bled steam is pumped into the feed water main to be returned to the boiler. In large steam turbine plants, several feed heaters are introduced.
- The process results in an improvement in the thermal efficiency of the plant.

This effect is accommodated in the use of the *stage efficiency*, where,

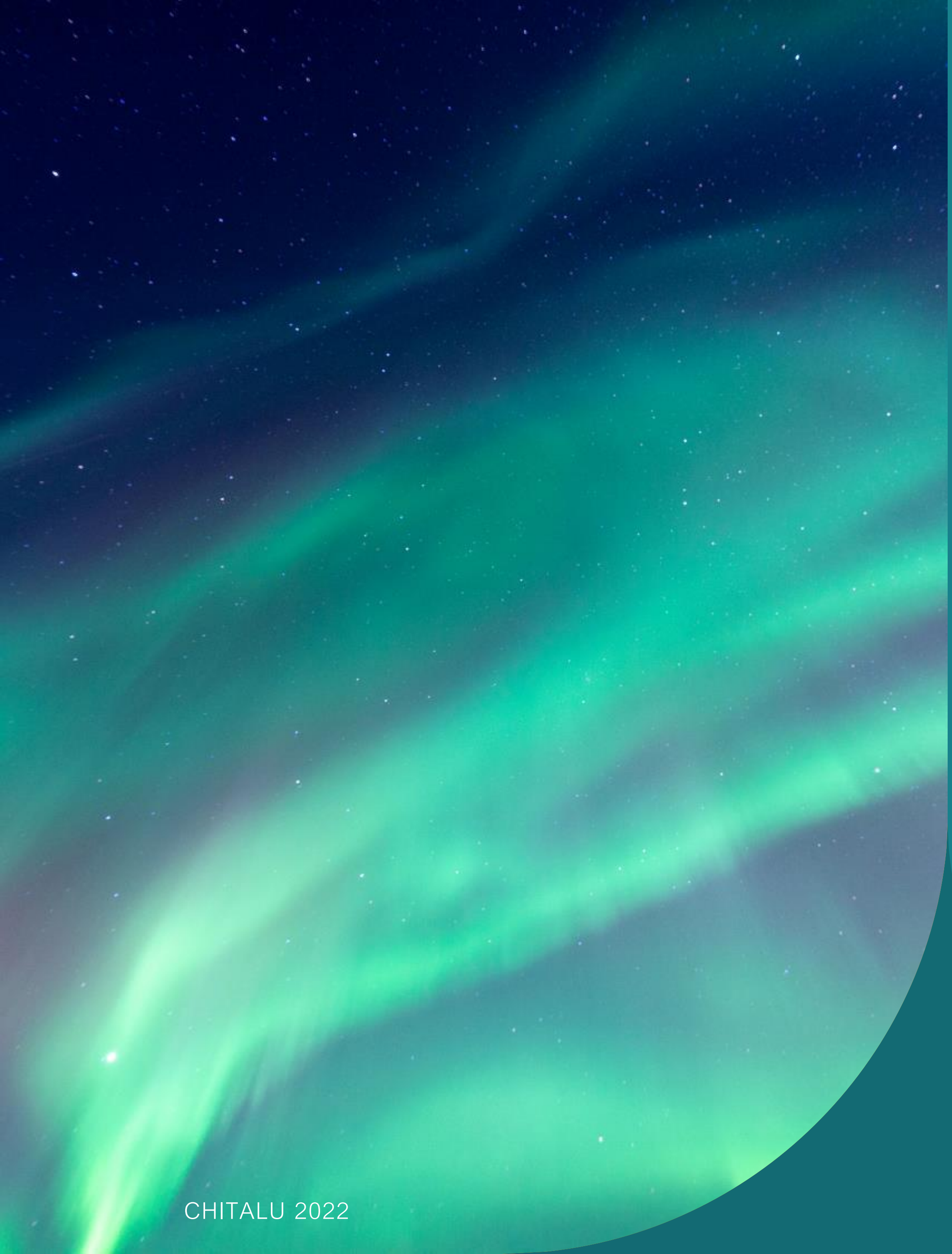
$$\text{Stage efficiency} = \frac{\text{actual enthalpy drop in stage}}{\text{isentropic enthalpy drop in stage}}$$

THE REGENERATIVE CYCLE



“Entropy increases. Things fall apart”

John Green



Thank You

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